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Harold P. Larson, D. Scott Davis,
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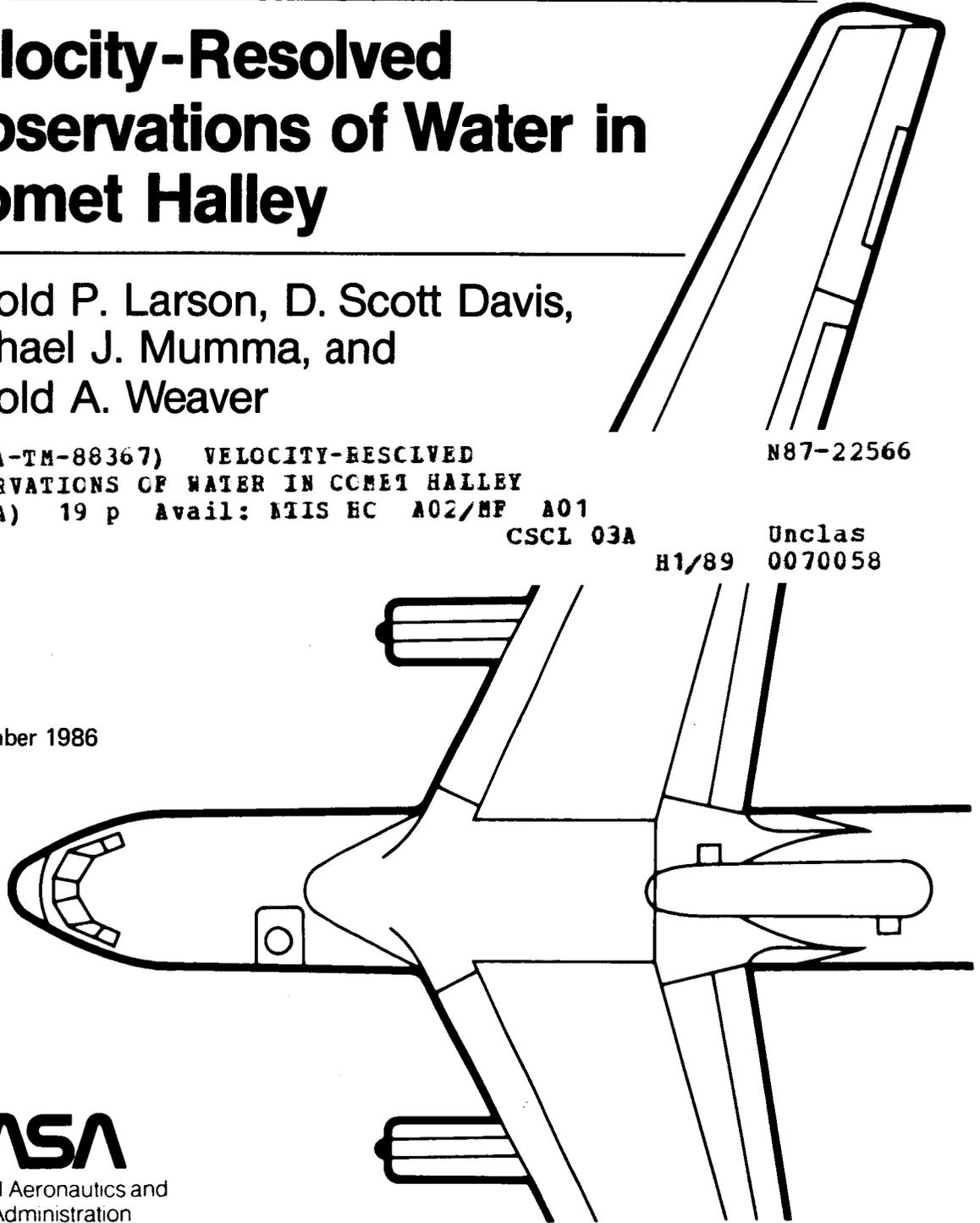
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H1/89   0070058

September 1986

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Harold P. Larson, Lunar and Planetary Observatory, University of Arizona, Tucson, Arizona
D. Scott Davis, Steward Observatory, University of Arizona, Tucson, Arizona
Michael J. Mumma, Goddard Space Flight Center, Greenbelt, Maryland
Harold A. Weaver, The Center for Astrophysical Sciences, Johns Hopkins University,
                  Baltimore, Maryland

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ABSTRACT

High resolution ($\lambda/\Delta\lambda\approx3\times10^5$) near-infrared observations of H_2O emission from Comet Halley were acquired at the time of maximum post-perihelion geocentric Doppler shift. The observed widths and absolute positions of the H_2O line profiles reveal characteristics of the molecular velocity field in the coma. These results support H_2O outflow from a Sun-lit hemisphere or the entire nucleus, but not from a single, narrow jet emanating from the nucleus. The measured pre- and post-perihelion outflow velocities were 0.9±0.2 and 1.4±0.2 km s^{-1}, respectively. Temporal variations in the kinematic properties of the outflow were inferred from changes in the spectral line shapes. These results are consistent with the release of H_2O into the coma from multiple jets.

I. INTRODUCTION

The detection of gaseous H_2O in Comet Halley from the NASA Kuiper Airborne Observatory (KAO) convincingly established that H_2O is a major volatile component of cometary matter (Mumma et al. 1986). That work also demonstrated that excitation of the H_2O v_3 vibration-rotation band in the coma is dominated by infrared fluorescence, a mechanism that only recently received theoretical attention (see e.g. Weaver and Mumma 1984). The combination of a realistic infrared excitation model and high spectroscopic sensitivity for studying near-infrared cometary H_2O bands from aircraft gives unprecedentedly detailed glimpses into other physical conditions in the coma. Weaver et al. (1986) used this diagnostic potential at moderate spectral resolution ($\lambda/\Delta\lambda \approx 3 \times 10^3$) to study temporal activity and spatial variations in Comet Halley's H_2O emission, and they correlated this information with other spectral data, including simultaneous observations of OH and continuum emission from the International Ultraviolet Explorer satellite (IUE). We present here very high resolution ($\lambda/\Delta\lambda \approx 3 \times 10^5$) observations of H_2O in Comet Halley. The positions and widths of the H_2O emission line profiles reveal characteristics of the velocity field in the coma.

II. OBSERVATIONS

The high resolution observations were made aboard NASA's Kuiper Airborne Observatory on UT 22 March 1986 from 16:30 to 17:50 using the University of Arizona Fourier transform spectrometer (Davis et al. 1980). The KAO was based in Christchurch, New Zealand to optimize post-perihelion

observations of Comet Halley. A cold filter limited the spectrometer's spectral bandpass from 3745 to 3830 cm^{-1}. This interval included most of the transitions in the H_2O v_3 band that would be excited by infrared fluorescence. The angular field-of-view (41" diameter) centered on the cometary nucleus corresponded to a spatial field of 2.2×10^4 km diameter at the comet's geocentric distance $\Delta=0.75$ a.u. The flight altitude of the KAO was maintained at 12.4 km where the average line-of-sight residual terrestrial H_2O abundance was about 10 prec. μm H_2O. A lunar comparison spectrum was recorded on UT 24 March 1986 to evaluate atmospheric and instrumental transmission factors.

A portion of the comet's spectrum is displayed in Figure 1. Thirteen H_2O lines were identified in the complete spectrum; these are listed in Table 1. The signal-to-noise (rms) ratio in the strongest observed line is about 80. The theoretical unapodized instrumental resolution (Rayleigh criterion) is 0.014 cm^{-1}, equivalent to a velocity width of 1.1 km s^{-1} at 3800 cm^{-1}. For comparison, the signal-to noise ratio in our pre-perihelion observations was about 40 and the instrumental velocity resolution was 3.2 km s^{-1} (Mumma et al. 1986). The improvement in our post-perihelion data is due in part to a smaller geocentric distance, but primarily it is a consequence of higher line intensities due to an increased H_2O production rate (Weaver et al. 1986). The cometary H_2O lines in Figure 1 are Doppler-shifted to shorter wavelengths because of the comet's geocentric velocity $\dot{\Delta} \approx -43$ km s^{-1}. This large value placed each cometary line on the far blue wing of the corresponding telluric H_2O absorption (see Figure 2). The full profile of each cometary line was therefore recorded with minimum interference from terrestrial H_2O. This spectrum

could not have been recorded at a ground-based facility because of complete obscuration of cometary features by telluric H_2O. Furthermore, nothing comparable was achieved from spaceborne infrared spectrometers because of their restriction to very low resolving powers [$\lambda/\Delta\lambda$=40 on the VEGA IKS experiment (Combes *et al.* 1986); $\lambda/\Delta\lambda$=70 on the VEGA TKS experiment (Krasnopolsky *et al.* 1986)].

The cometary H_2O line positions in Table 1 are expressed as absolute wavenumbers in vacuum. They were corrected for the refractive index of air under experimental conditions and for the finite sizes of the signal and reference beam apertures. To remove possible systematic error due to uncertainty associated with the actual wavelength of the spectrometer's reference laser, we compared the positions of isolated H_2O absorption lines observed in the lunar comparison spectrum with interferometrically measured laboratory values. Small systematic differences, typically +0.006 cm^{-1} or less, were fit to a low order polynomial correction function that was applied to both the lunar and cometary spectra. This procedure therefore tied the final absolute wavenumber calibration of the astronomical spectra to the best available laboratory measurements [Camy-Peyret *et al.* (1973), who claim an absolute accuracy better than ±0.003 cm^{-1}, or ±0.24 km s^{-1} at 3800 cm^{-1}].

The absolute calibration of the cometary H_2O line intensities is not essential for this paper. We note, however, that our absolute intensities for the lines in Table 1 lead to a water production rate $Q_{H_2O} \approx 1 \times 10^{30}$ mol s^{-1}.

III. RESULTS

a) Nucleocentric H_2O Velocity

Three velocities contribute to the observed positions of the cometary lines in Table 1: (1) the motion of the comet relative to the Earth (geocentric component); (2) the observatory's motion due to the Earth's rotation and the KAO's flight track (topocentric component); and (3) the net outflow velocity of H_2O molecules from the nucleus (nucleocentric component). The geocentric velocity component was -43.25 km s^{-1} (Edberg 1986; negative velocities are directed towards the Earth). The topocentric velocity v_{KAO}=-0.25 km s^{-1} was calculated from the KAO flight log. Wavenumber corrections for these two velocity components were applied to each of the observed H_2O lines. The calculated nucleocentric H_2O line positions (see Table 1) should then differ from laboratory rest positions only if there is a net outflow of H_2O molecules either towards or away from the Earth. The weighted average of these differences is -0.21±0.12 km s^{-1}. A similar treatment of our pre-perihelion data (Mumma *et al*. 1986) yields -0.18±0.15 km s^{-1}. Both measurements indicate that the H_2O outflow distributions, averaged over the spectrometer's field-of-view, have no dominant velocity components along the Comet-Earth line-of-sight. The quoted 1σ errors suggest that there may be small blue shifts to the distributions, but more conservative error estimates are consistent with no shifts.

These results are surprising. The maximum H_2O outflow is expected to occur towards the Sun with possibly a small phase lag angle ϕ with respect to the sub-solar point because of nuclear rotation. The Sun-comet-Earth angles at the time of our pre- and post-perihelion observations

were 55° and 66°, respectively. The viewing geometry would then have placed the maximum H_2O outflow at angle $\theta = 55°-\phi$ with respect to the comet-Earth line-of-sight at pre-perihelion and at $\theta = 66°+\phi$ at post-perihelion. We estimate that $\phi \approx -8°$ from our nucleocentric velocity measurements. This value implies that (1) the H_2O outflow actually was spatially re-stricted to a direction along or near the Sun-comet axis, or (2) the outflow distribution only appeared to be directed along this axis because of velocity averaging in the spectrometer's field-of-view. The first possibility is excluded for two reasons. First, if the outflow was re-stricted to a single, narrow jet with $\phi \approx -8°$ and $v_t \approx 1$ km s^{-1}, the observed pre- and post-perihelion nucleocentric velocities should have been about -0.5 km s^{-1}, contrary to the observed values. Second, the natural width of the cometary lines for such an outflow would.be rather narrow, contrary to the observed line widths which are discussed in the next section. The outflow must therefore be more widely dispersed. The above measurements do not uniquely constrain the spatial extent of the outflow, but they do require that the distribution of velocities in the spectrometer's field-of-view produce very small or no net nucleocentric velocity components for both the pre- and post-perihelion viewing geometry. Several possible outflow distributions consistent with this constraint are discussed in the next section.

b) The Gas Velocity Field in the Coma

The outflow distribution will influence the observed H_2O spectral line profiles at sufficiently high resolution. In general, the observed line profile is the convolution of the comet's velocity dispersion function

(VDF) with the experimental instrumental line shape (ILS). The data in Figure 2 illustrate H_2O line profiles from our high resolution spectra. The ILS for the pre-perihelion data was a sinc function distinguished by its very prominent side lobes; its width defined by the Rayleigh criterion was 3.2 km s^{-1}. The observed cometary line profile is so similar to the ILS that the width of the VDF must be substantially less than 3.2 km s^{-1}. The ILS for the higher resolution post-perihelion observations was also a sinc function (width=1.1 km s^{-1}). However, the observed cometary line profile has a width of 2.4 km s^{-1} and the side lobes are completely suppressed. The cometary line is therefore at least partially resolved, and the width of the VDF must be larger than that of the ILS. More stringent limits to the velocity width result from applying deconvolution analysis to the observed line profiles. We considered two simple distributions: (1) outflow into a Sun-facing hemisphere oriented approximately perpendicularly to the comet-Earth line-of-sight; and (2) a spherically symmetric outflow. Both allow projected velocity components from $-v_t$ to $+v_t$ along the line-of-sight without producing a net nucleocentric velocity shift. The shape of the VDF is determined by the actual distribution of velocities in the outflow. For this preliminary analysis we used rectangular functions (FWHM=$2v_t$) to represent hemispherical or spherical uniform outflow. We convolved rectangular functions having different widths with the ILS and compared the calculated profiles with the observed cometary lines. We found that the maximum width compatible with the pre-perihelion line profile was 1.8±0.4 km s^{-1} and the minimum width required for the post-perihelion data was 2.7±0.4 km s^{-1}. The uncertainties in v_t were obtained by propagating the 1σ errors in the measured line widths through the

numerical convolution. These measurements imply that the VDF's may have been different for our two high resolution spectra. This difference was confirmed in the following manner. The post-perihelion cometary line profile in Figure 2 was Fourier transformed at the lower resolution of the pre-perihelion data. It was clearly broader than either the theoretical ILS or the observed H_2O line at pre-perihelion, and its side lobes were not fully developed. This comparison demonstrated independently that the natural width of the cometary H_2O lines was larger during the post-perihelion observations. This difference may be due to changes in the shape of the VDF, to an increase in the value of v_t, or both. The observed line profiles could also be influenced by temporal changes in the comet's brightness. In particular, apodization (i.e broadening) of the profile would result if the comet's brightness decreased during data acquisition. However, we have no independent evidence to support this possibility, and it is equally probable that the comet could have brightened during the scan. For this preliminary analysis we interpret the observed line profiles in terms of rectangular VDF's differing only in width. Our estimates of v_t become 0.9 ± 0.2 and 1.4 ± 0.2 km s^{-1} for the pre- and post-perihelion spectra, respectively. These values can be compared to theoretical predictions of about 1 km s^{-1} and to the *in situ* measurement of 0.90 ± 0.20 km s^{-1} from the mass spectrometer on Giotto (Krankowsky *et al*. 1986).

IV. SUMMARY

Our spectroscopic measurements support the following description of molecular outflow from Comet Halley.

1. Water appears to be widely dispersed around the nucleus. One plausible distribution is outflow into a presumably Sun-facing hemisphere, although spherically symmetric outflows cannot be excluded. The data are not compatible with outflow into any narrow solid angle.

2. The measured pre- and post-perihelion H_2O terminal velocities were 0.9 ± 0.2 and 1.4 ± 0.2 km s^{-1}, respectively. Since they apply to nearly the same heliocentric distance of the comet (≈ 1 a.u.), their difference may indicate an unexpected asymmetry in the dynamic properties of the pre- and post-perihelion outflows. However, the shape of the VDF must be constrained by a more detailed deconvolution analysis in order to pursue this interpretation.

3. The outflow exhibited temporal variations as evidenced by changes in the natural width of the observed spectral lines. This variability may be diagnostic of some kinematic property of the outflow, but more analysis is required to identify it. It is significant to note that the water production rates derived from these infrared spectra also showed strong temporal variability, and, in particular, they were significantly enhanced in the post-perihelion data (Weaver *et al.* 1986).

The above description is consistent both with general expectations concerning the release of volatile constituents from cometary matter and with more detailed results from other recent observations of Comet Halley. For example, direct images of Comet Halley from Giotto revealed multiple jets releasing material into most of the Sun-facing hemisphere (Keller *et al.* 1986). These jets plausibly sustain the field-averaged distribution deduced from our infrared spectra and they also account for the temporal variations that appear in many kinds of measurements of Comet Halley. We

observed large, rapid variations in the H_2O line intensities throughout our program of airborne observations of Comet Halley (Weaver *et al.* 1986), and others noted strong outbursts on time scales of a few hours [e.g. ground-based images of dust outbursts (Sekanina and Larson 1986); dust and gas spectrophotometry from IUE (Festou *et al.* 1986)]. This activity emphasizes the need to develop more realistic physical models of comets. We have demonstrated that remote infrared spectroscopic measurements can contribute to this task by providing measurements of kinematic conditions in the coma. This capability can be refined and applied to other comets which will not be as intensively studied as was Comet Halley.

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FIGURE CAPTIONS

Figure 1. A portion of the velocity-resolved airborne spectrum of H_2O in Comet Halley. The line intensities are uncorrected for instrumental and atmospheric transmission factors. The accompanying lunar comparison spectrum indicates residual telluric H_2O absorptions. The plus signs designate cometary H_2O lines assigned to the 001-000 vibration band, and the crosses indicate H_2O transitions assigned to the "hot" 011-010 band. The quantum numbers of the upper and lower states accompany each cometary line. The corresponding transitions in the 001-000 band in absorption in the Earth's atmosphere are marked with arrows on the lunar wavenumber axis. The cometary observations were scheduled at nearly maximum geocentric Doppler shift, thus accounting for the wide separation of the cometary and telluric features. The "hot" lines in the comet's spectrum do not appear in the lunar spectrum; they are almost certainly pumped in the 011-000 band followed by fluorescence in the 011-010 band. Some strong H_2O absorption lines in the 001-000 band in the lunar spectrum without accompanying, Doppler-shifted cometary emission lines are marked with their quantum numbers. These features arise from higher levels that are rotationally relaxed in the cometary coma. Telluric lines belonging to the 100-000 band are marked with asterisks and are not expected to be present in the comet's spectrum.

Figure 2. Comparison of pre- and post-perihelion H_2O emission line profiles from Comet Halley. The post-perihelion data are characterized by higher SNR and higher instrumental resolution. The pre-perihelion line

profile is unresolved. The structure at the base of the profile is due to the side lobes of the ILS. The post-perihelion line profile lacks these side lobes because the natural velocity width of the cometary line is at least partially resolved. The ordinate scale indicates relative instrumental transmission in the lunar spectrum. The cometary lines are arbitrarily scaled to the same height for direct comparison of their profiles.
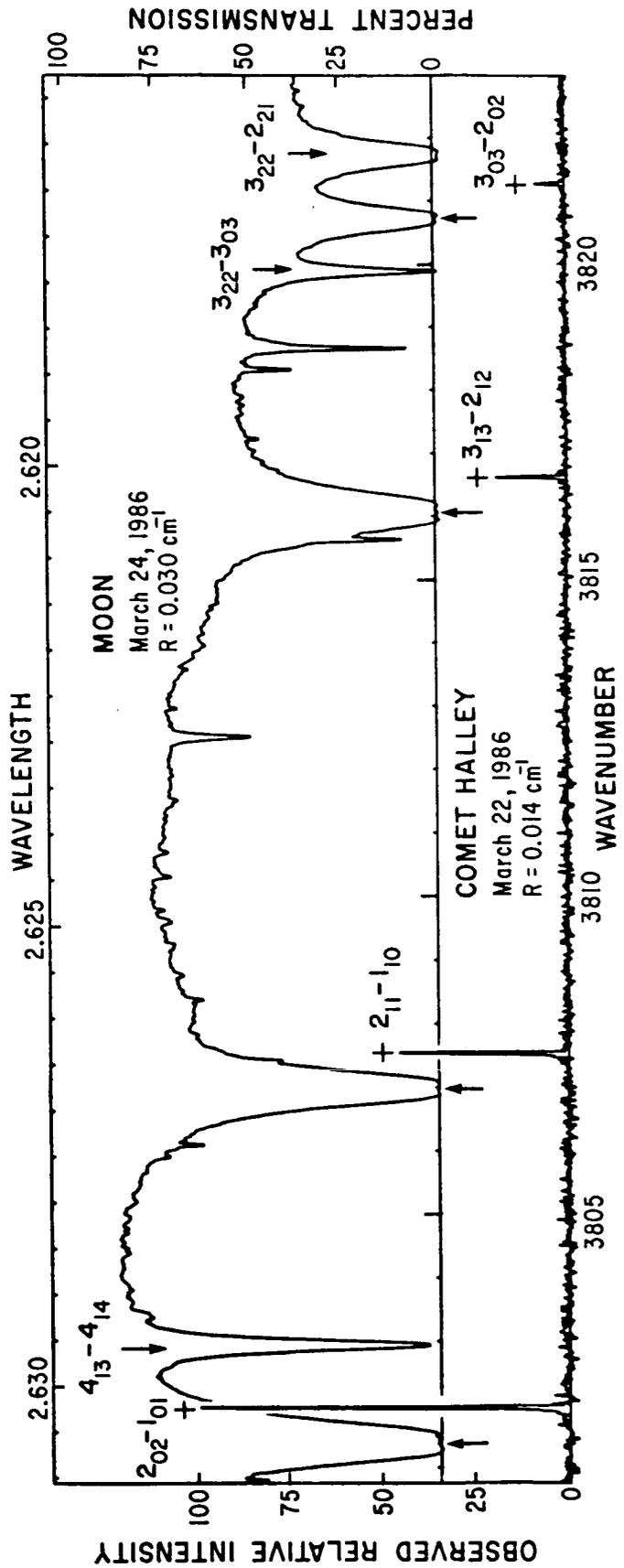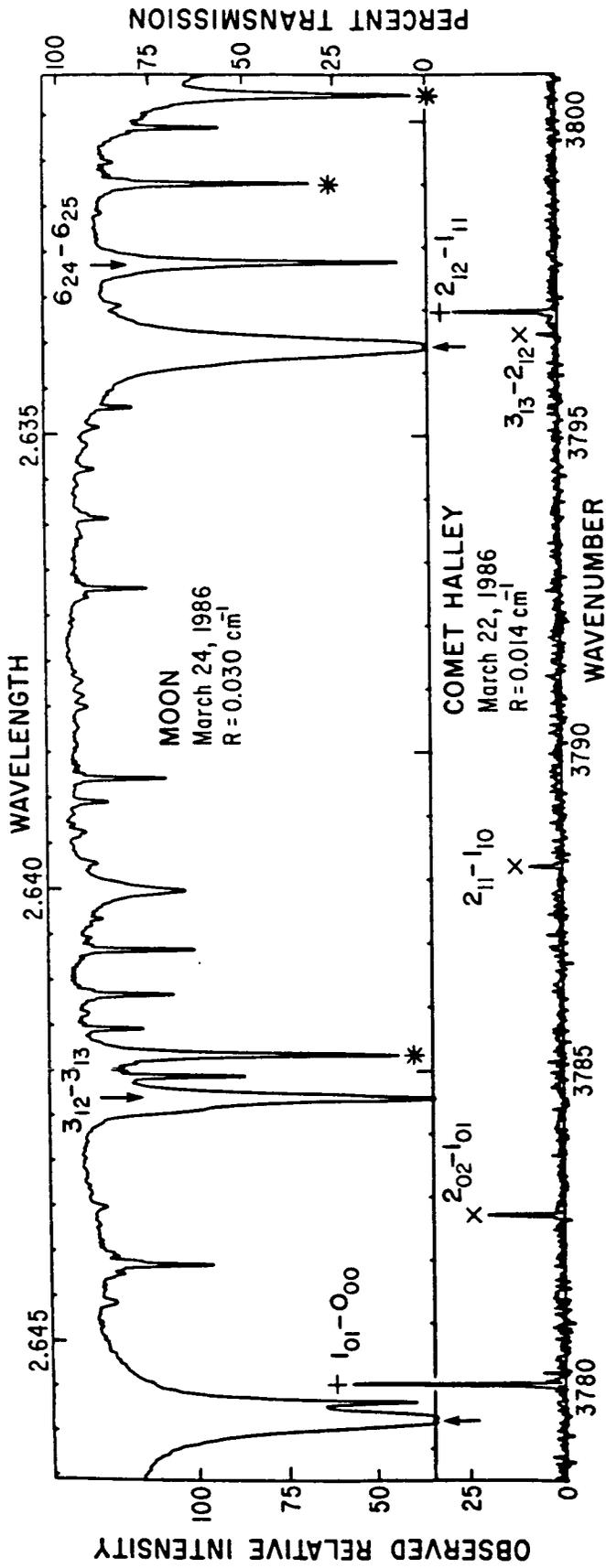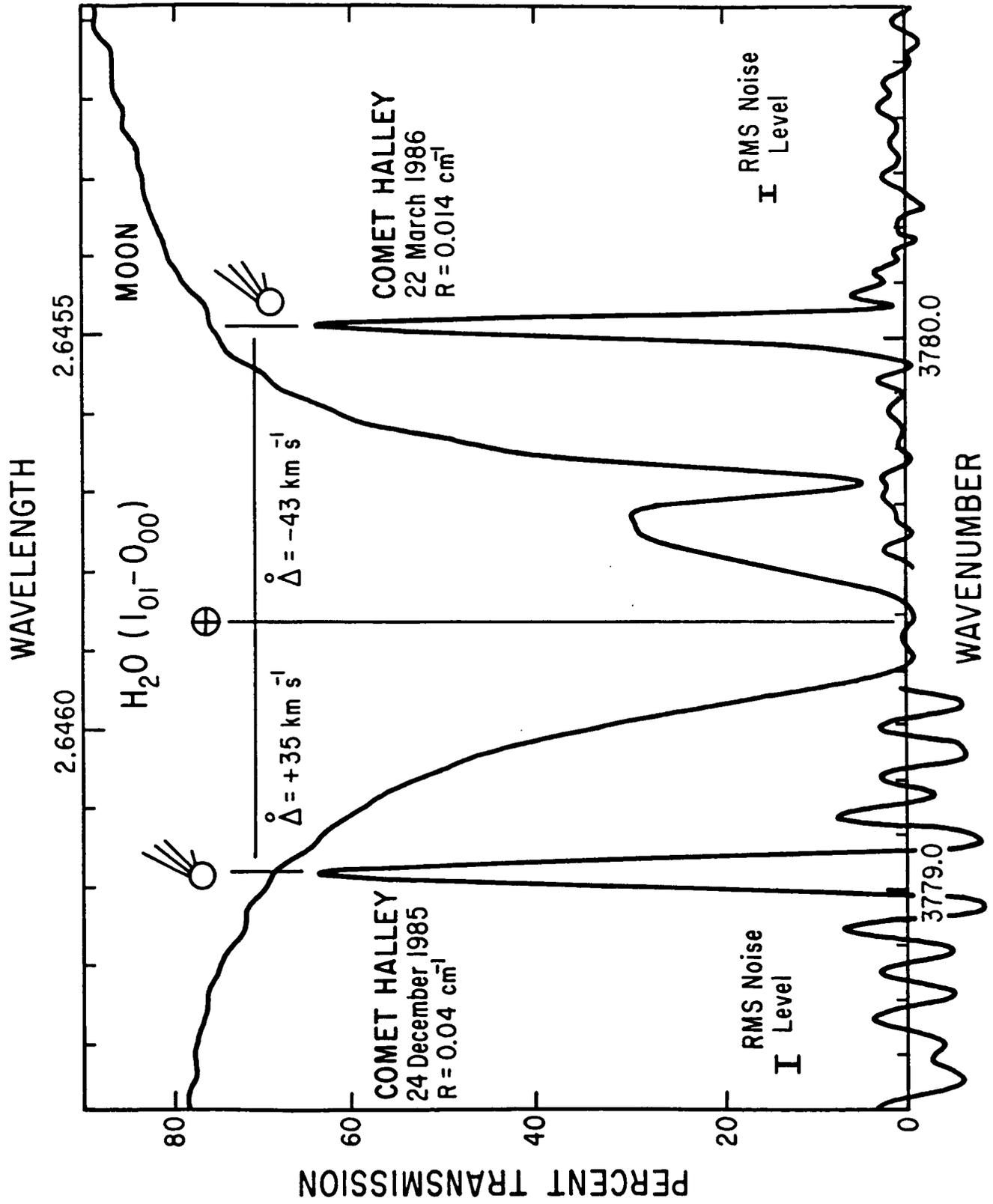
Figure 1

Figure 2

TABLE 1

H_2O EMISSION LINES FROM COMET HALLEY

| Transition | | Line Position | | | Relative |
Vibration	Rotation	Observed (cm-1)	Nucleocentric (cm-1)	Rest (cm-1)[1]	Intensity
001-000	$1_{11}-1_{10}$	3749.878±0.005	3749.332	3749.330	130±70
001-000	$2_{20}-2_{21}$	3752.757±0.006	3752.211	3752.213	49±26
001-000	$1_{10}-1_{11}$	3760.393±0.004	3759.846	3759.845	51±11
001-000	$2_{11}-2_{12}$	3770.440±0.004	3769.891	3769.890	37±8
001-000	$1_{01}-0_{00}$	3780.045±0.002	3779.496	3779.494	42±3
011-010	$2_{02}-1_{01}$	3782.733±0.008	3782.183	3782.179	12±1
011-010	$2_{11}-1_{10}$	3788.222±0.009	3787.672	3787.666	5±1
011-010	$3_{13}-2_{12}$	3796.634±0.016	3796.080	3796.083	7±1
001-000	$2_{12}-1_{11}$	3796.994±0.003	3796.442	3796.440	18±1
001-000	$2_{02}-1_{01}$	3801.973±0.002	3801.420	3801.420	100±5
001-000	$2_{11}-1_{10}$	3807.569±0.002	3807.016	3807.015	44±3
001-000	$3_{13}-2_{12}$	3816.649±0.004	3816.094	3816.092	27±3
001-000	$3_{03}-2_{02}$	3821.295±0.009	3820.740	3820.739	14±2

[1] From Camy-Peret et al. (1973)

1. Report No. NASA TM-88367	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle VELOCITY-RESOLVED OBSERVATIONS OF WATER IN COMET HALLEY		5. Report Date September 1986
		6. Performing Organization Code
7. Author(s) Harold P. Larson,* D. Scott Davis,† Michael J. Mumma,‡ and Harold A. Weaver§		8. Performing Organization Report No. A-86410
		10. Work Unit No.
9. Performing Organization Name and Address *Lunar and Planetary Observatory, Univ. of Arizona, Tucson AZ 85721, †Steward Observatory, Univ. of Arizona, Tucson, AZ 85721, ‡Goddard Space Flight Center, Greenbelt, MD 20771, §Center for Astrophysical Sciences, Johns Hopkins Univ., Baltimore, MD 20771		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		
		14. Sponsoring Agency Code 352-02-03

16. Abstract

High resolution ($\lambda/\Delta\lambda \approx 3\times10^5$) near-infrared observations of H_2O emission from Comet Halley were acquired at the time of maximum post-perihelion geocentric Doppler shift. The observed widths and absolute positions of the H_2O line profiles reveal characteristics of the molecular velocity field in the coma. These results support H_2O outflow from a Sun-lit hemisphere or the entire nucleus, but not from a single, narrow jet emanating from the nucleus. The measured pre- and post-perihelion outflow velocities were 0.9 ±0.2 and 1.4 ±0.2 km s^{-1}, respectively. Temporal variations in the kinematic properties of the outflow were inferred from changes in the spectral line shapes. These results are consistent with the release of H_2O into the coma from multiple jets.

17. Key Words (Suggested by Author(s)) Comet: Halley Infrared: spectra Molecular processes: water vapor	18. Distribution Statement Unlimited Subject category - 89		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 18	22. Price* A02